Feasibility Studies of Operating KrF lasers at Ultra-Narrow Spectral Bandwidths for 0.18 μm Line Widths

Alex I. Ershov, Thomas Hofmann, William N. Partlo, Igor V. Fomenkov, George Everage, Palash P. Das, David Myers

Cymer, Inc., 16750 Via Del Campo Ct. San Diego, CA 92127

ABSTRACT

The use of higher NA lenses in the next generation 248 nm microlithography systems sets tight requirements on the spectral properties of the laser. The present paper discusses recent advances in KrF excimer laser spectral line-narrowing technology. General principals of line-narrowing are discussed as well as its implementation on excimer lasers. KrF lasers are characterized by the fact that its gain exists for a very short period, typically equivalent to about 3 - 6 round trips of light in the laser resonator. Therefore, the spectral line narrowing scheme should be capable of effective line-narrowing on a single light pass. The basic line-narrowing scheme might include a diffraction grating working in Littrow configuration with a prism beam expander. The single pass line-narrowing efficiency should be enough to achieve a spectral bandwidth (FWHM) of about 0.8 pm with 95% of the energy concentrated within 3.0 pm. This spectral width is generally sufficient for present day steppers and scanners. However, future microlithography systems providing critical dimensions of 0.18 μm or less will require laser with narrower spectral width. Therefore, the single pass line-narrowing efficiency has to be increased. However, the design of the line narrowing scheme should not compromise other beam parameters that are equally relevant in microlithography. These parameters include: laser efficiency, beam size, coherence and divergence.

The move towards higher NA is also coupled with move towards higher throughput from scanners. As a result, the laser's power and dose stability should increase along with a decrease in linewidth. We demonstrate that such scaling of spectral widths, power and repetition rates is possible by re-visiting some of the dynamics of evolution of laser spectrum and stability of laser discharge. In the following, we present results of several optical configurations, that result in spectral widths between 1.0 and 2.0 pm (95% integrated linewidth). The optical configurations are derivatives of Cymer's standard Littrow grating and prism expander configuration. Thereby, the other parameters (beam size, coherence, etc.) are not impacted. Simultaneously, we provide results of scaling a laser to 2 kHz with a dose stability of less than ± 0.5% over a 16ms window. The resulting laser is now capable of meeting the technical requirements of the next generation microlithography scanners.

Keywords: DUV lithography, KrF excimer laser, line-narrowing

1. INTRODUCTION

Deep-Ultra-Violet (DUV) lithography using 248 nm KrF laser is now going from pilot to mass production in semiconductor plants around the world as the chip makers are now producing 686-class micro-processors and 64 Mb DRAMs that require less then 0.25 μm critical dimensions (CD). As the chip makers gear up for 256 Mb DRAM production and start focusing on 1 Gb products, much smaller CD is required, typically of less then 0.18 μm[1]. Recent reports[2,3] show that such a task is possible using KrF systems when advanced resolution enhancement techniques like phase shifting and off-axis illumination are used[4]. The problem, however, is that it is very difficult to achieve any chromatic correction at 248 nm as most of optical materials which can be used to construct the imaging lens exhibit strong dispersion in

that region. Therefore, the refractive imaging systems set limits on the maximum spectral bandwidth of the KrF laser. For example, in order to produce 0.18 μm feature sizes using quartz refractive lens, the bandwidth of the KrF lasers should be reduced from currently available 0.8 pm (full width at the half maximum - FWHM) to less then 0.4 – 0.5 pm. The concentration of energy is also very important so that the band containing 95% of laser energy should be reduced from current number of 3 pm to less 2 pm.

The 248 nm KrF excimer laser has a natural bandwidth of approximately 300 pm (FWHM). That line has to be narrowed by almost three orders of magnitude. If the spectral bandwidth after the single round trip of light in the resonator is $\Delta\lambda_{1,}$ then the bandwidth $\Delta\lambda_f$ after *n* round trips can be generally described by the following equation:

$$\Delta\lambda_f = \Delta\lambda_1 / \sqrt{n}\ . \qquad (1)$$

The gain media of KrF lasers used in lithography applications typically exists for about 50 ns or less, and the round trip type is typically 6 - 8 ns. That means that there are only 6 - 8 round trips of light per laser pulse. Therefore, the spectrum-narrowing technology used in the laser should be capable of bringing the spectrum down to close to one pm level in just a single round trip of light. That is quite different from many other types of lasers which can allow multiple passes of light before it gets narrowed to the required bandwidth. At the same time, the overall lithography laser has to be very reliable, capable of producing light 'on-demand' 24 hours a day with very little un-planned maintenance. All these factors have to be considered when designing and engineering line-narrowing techniques.

2. SPECTRALLY LINE-NARROWED KrF LASER

2.1 Time evolution of spectrum

There exists several line-narrowing techniques to spectrally narrow excimer lasers. These include, for example, the use of a combination of prisms, etalons and diffraction gratings placed inside the laser optical cavity. The technique of choice is one that produces the narrowest spectral width without compromising other beam properties or reliability. One of the basic line-narrowing schemes capable of meeting the above requirements is shown in Fig.1. The laser includes a gas chamber with a tilted windows to avoid reflection. The laser optical cavity is created by a diffraction grating working in Littrow configuration and a partially reflecting output coupler. Diffraction grating also works as dispersive element. A prism beam expander is placed before the grating and used to expand the beam before it hits the grating in order to improve the dispersion efficiency of the grating. Two apertures on each side of the chamber are used to select the required wavelength. With this scheme it is possible to achieve a spectral width (FWHM) of about 0.8 pm at the repetition rate of up to 1000 Hz with an average power of up to 10W. The 95% of the output energy (95% integral) of this laser is concentrated within 3pm band. Fig.2 shows a typical spectrum of the laser with the basic configuration described above. The spectrum was measured with a Cymer made high resolution grating spectrometer with a slit function of 0.12 pm. This spectrum is a time integrated laser spectrum.

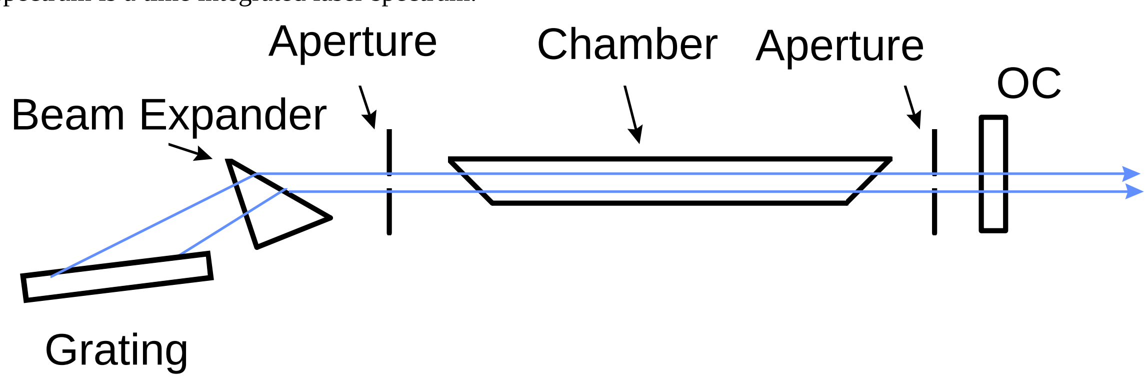

Fig.1. The basic scheme of line-narrowed KrF excimer laser.

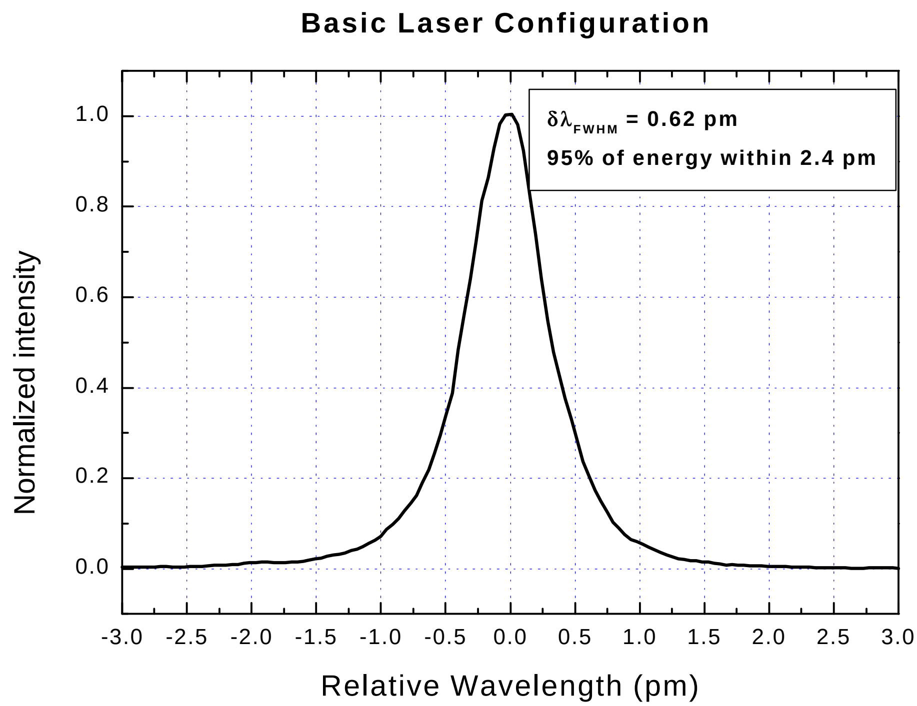

Fig.2. Spectrum of the KrF laser in the basic configuration. Pulse energy is 10 mJ. Center wavelength is 248.300 nm.

However, according to Equation (1), the spectrum is not constant during the pulse, but instead it is broader at the beginning and narrower at the end of the pulse.

Fig.3 shows the measured spectral width during the duration of a pulse. Fig. 3a shows two curves. One curve (pulse shape) is the actual laser intensity in time $I(t)$. The second curve is the total energy emitted by a laser from the beginning of the pulse t_0 till the moment t and is actually equal to integral $\partial I(t)$. About 95% of the pulse energy is emitted during the first 50 ns of the pulse. Fig. 3b shows the time dependence of the laser spectrum during the pulse. One can see that at the beginning of the pulse, the spectrum is quite broad and that it narrows during the duration of the pulse. For example, at the 5^{th} ns, the FWHM value is about 1.3 pm and 95% of the spectral energy is within 2.8 pm. As the light travels back and forth in the cavity, the spectrum quickly narrows, in agreement with Equation (1). For example, at the 20^{th} ns, the FWHM is about 0.6 pm and 95% of the spectral energy is within 1.4 pm. These numbers are actually better then corresponding numbers for the time integrated spectrum. Unfortunately, at this time, the laser has emitted almost 60% of its energy in that pulse.

Fig.4 shows the evolution of the actual spectrum of the laser during the pulse generation. This figure has 12 different graphs. Each graph has two curves. The curve shown in dotted line is the time-integrated spectrum over the whole pulse, and the solid curve is the actual spectrum at that particular moment. The data is taken from 2.5 ns to 57.5 ns from the beginning of the pulse with the step of 5 ns. The time resolution is about 2.5 ns. The exact time is shown on each graph as well as a percentage of total pulse energy emitted by the laser from the beginning of the pulse. There is a noticeable shift of the spectrum to the red during the first 10 ns of the pulse. The maximum value of the shift is about 0.1 pm, and the shift disappears by the time the pulse intensity reaches its maximum at t = 10 ns. Another interesting feature seen on both Fig.3b and Fig.4 is that the 95% integral actually increases at the very end of the pulse for t > 45 ns.

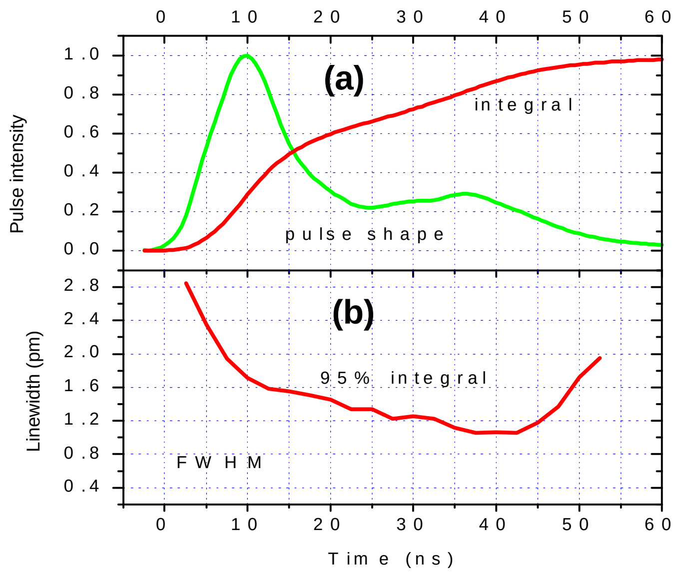

Fig.3. Laser pulse shape and its integral (a) and temporal dependence of the spectral FWHM and the bandwidth containing 95% of laser momentary power.

However, the FWHM does not seem to increase. Fortunately, by this time more than 90% of the laser energy in that pulse has been emitted. Therefore, the effect of this increase on the time integrated spectrum is insignificant. There are no previous reports about such abnormal time dependence of spectral widths. However, time-resolved divergence measurements on excimer beams in other laboratories[5] have revealed similar abnormal behavior. The broadening of the spectrum might be due to some plasma induced optical effects in the discharge area developing at the end of the laser pulse. For the present configuration this effect is insignificant but, this effect, however, might become very important when attempts are made to reduce the spectral width by stretching the pulse.

2.2 Spatial characteristics of spectrum

Normally, the spectrum is measured by sampling the full laser beam. This is the normal way of characterizing the spectrum as the beam is thoroughly mixed before it illuminates the exposure lens. However, it is instructive to measure spectral properties of the different parts of the beam to understand the line-narrowing processes. Fig.5 shows the results of such measurements. In this experiment the rectangular laser beam of about 16 mm high and 3.5 mm from the output of the laser is sampled through a vertical slit of about 0.3 mm wide an 16mm tall. The spectrum of the light in this slice of beam is then measured. The slit is scanned horizontally across the beam. The spectra obtained for each slice is shown in Fig. 5. The dotted curve is the spectrum of light uniformly sampled from the whole beam. One can see, that the spectrum of a vertical slice is actually narrower than of the whole beam but that the spectra measured for the left and right portions of the beam have some shift from the center wavelength. The shift is only observed in horizontal direction and is connected with an asymmetry in that direction created by diffraction grating. This shift causes the broadening of the spectrum. It might be attractive to reduce the shift to reduce the spectral width. A simple technique is just to vignette the edges of the beam with an aperture. Unfortunately, this approach would lead to significant reduction in efficiency and therefore not practical. Another approach would be to try to shift these individual spectra back to the center wavelength so that total spectral width would be the same as the spectral width of individual slice.

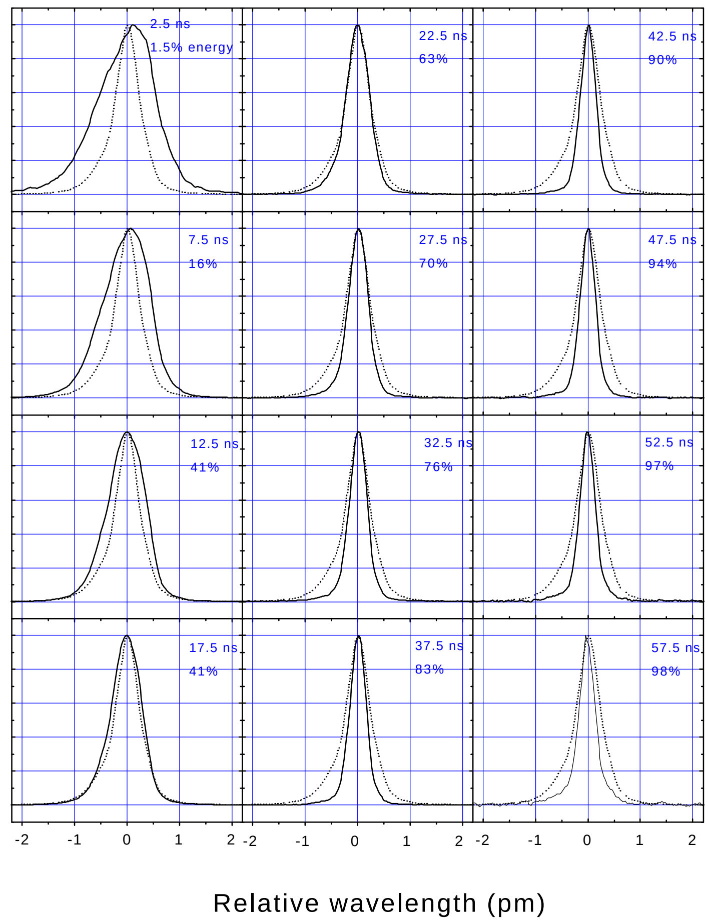

Fig. 4. Laser spectra at different times during the laser pulse. The numbers on each graph show the time from the beginning of the pulse and percentage of total pulse energy already emitted by that time.

2.3 Spectral data

In this paper we present three new optical configurations based on the aforementioned investigations. Fig. 6 shows comparison of these configurations (which we would call configuration A, B, and C) with the basic scheme. The results presented in Fig.6 are obtained using the same gas chamber and pulse power module @ 10mJ, so that effect of different optical setup can be clearly seen. All the data presented here are the raw (convolved) data measured with 0.12 pm grating spectrometer.

As one can see from Fig. 6, the basic scheme results in a FWHM of 0.62 pm with 95% of energy concentrated in 2.4 pm range. Configuration A reduces the FWHM down to 0.48 pm and 95% energy integral to 1.6 pm. Configuration B improves the FWHM further, down to about 0.37 pm, and 95% integral value down to 1.35 pm. Configuration C does not improve the FWHM value as compared with configuration B, but does reduce the 95% integral by another 30% down to 0.93 pm. This means that essentially all the light emitted is within a spectral width of less than 1 pm! Such spectral width reduction is achieved without a decrease in efficiency.

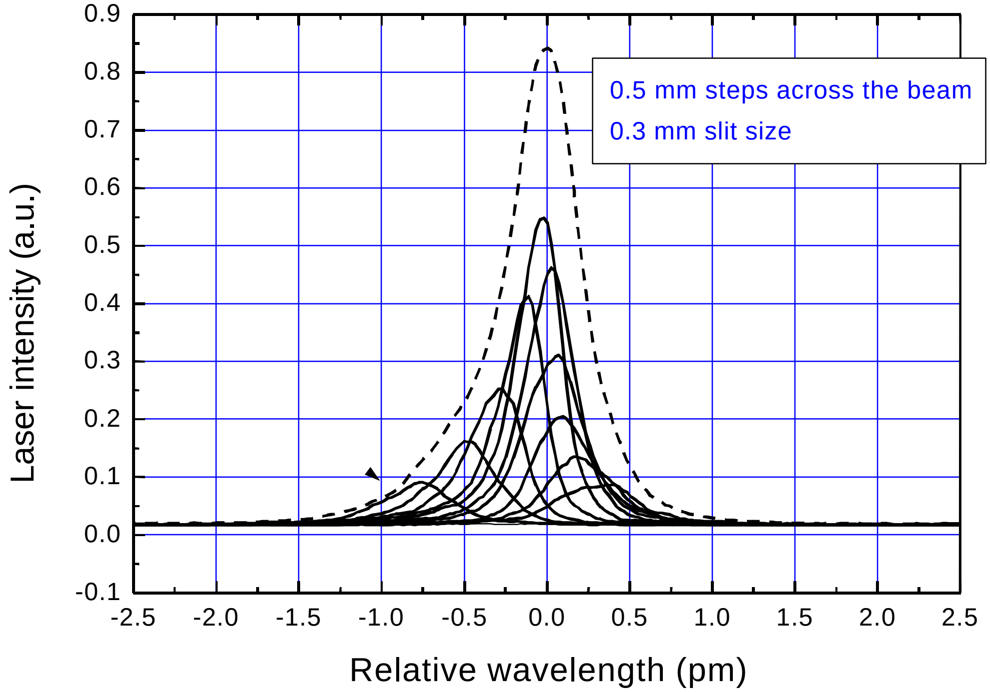

Fig.5. The spectra of different portions of the laser beam. Each solid curve is measured with vertical slit cutting a narrow vertical slice of the beam. As the slit is scanned over beam from one side to another, the spectrum shifts from short wavelength to long wavelength.

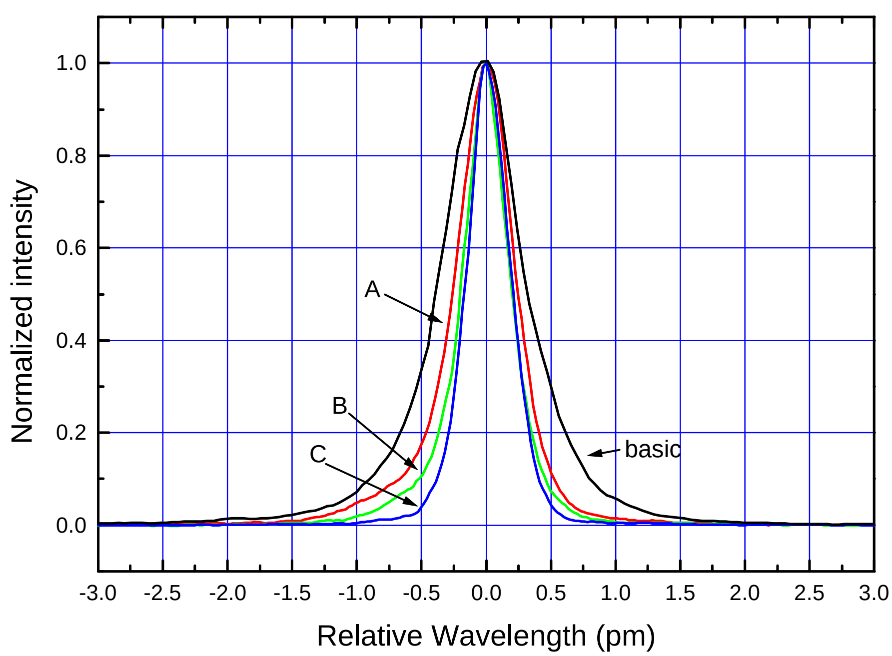

Fig.6. Comparison of the spectral bandwidth of the laser in basic configuration with new configurations A, B, and C.

3. Stable 2000 Hz operation for increased throughput

Besides narrow spectral width, the next generation scanner will require higher repetition rate and better dose stability than the present generation laser. That issue has been addressed as well.

The operating range of the laser was extended from 1 kHz to 2 kHz without increasing the outside chamber dimensions. This was accomplished by an improved pre-ionization scheme and by optimizing the electrical field distribution in the discharge region to minimize down-stream arcing. The new chamber operates arc-free at 2 kHz with a low clearing ratio, using the same blower configuration and blower power as the original 1 kHz chamber[6].

The discharge stability of excimer lasers normally decreases at high repetition rates due to an accumulation of the acoustic background in the chamber. A common solution for this problem is the implementation of acoustic absorbing materials in the laser chamber[7]. These materials, however, can introduce contaminants into the laser gas and render the halogen passivation process more difficult. In this work the discharge stability was addressed in an alternative way by redesigning the electrical excitation circuit. In simplified terms, discharge instabilities require a certain time to fully develop. The faster the excitation system the less will discharge instabilities impact laser performance. This fact is utilized in the present 2000 Hz laser.

The dependence of the pulse energy and its statistical energy fluctuation (3sigma) is displayed in Fig. 7. The laser was operated in the constant charge voltage mode. The averaged pulse energy is virtually independent of the repetition rate and varies by about 0.5 mJ. The pulse-to-pulse variations as seen in 3 sigma gradually increase with the repetition rate and show some structure. However, even up to 2 kHz, the 3sigma energy stability is less than 4%.

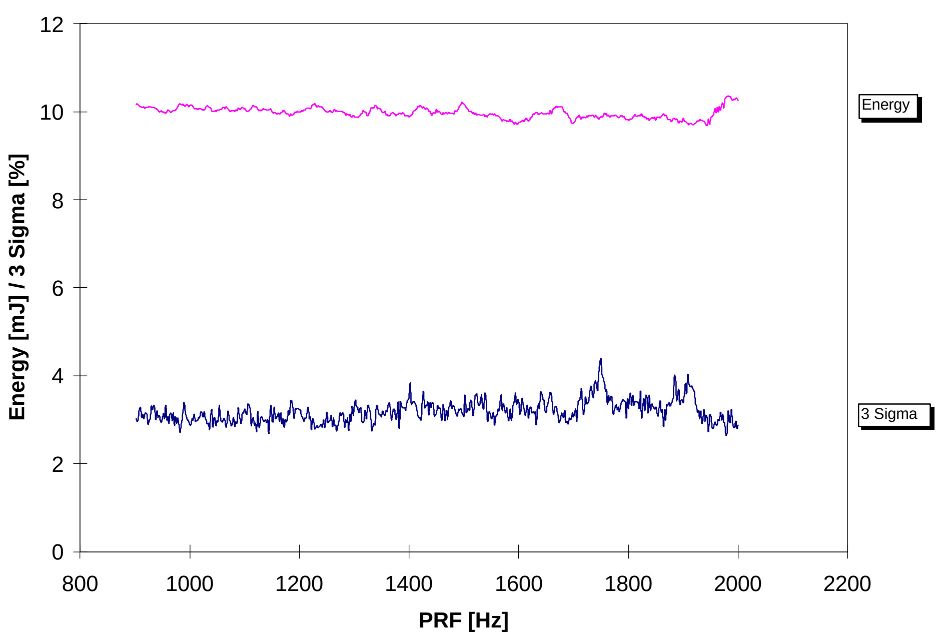

Fig. 7. The dependence of pulse energy and its 3 σ fluctuation on the laser repetition rate. The laser is run in constant high voltage mode.

The most important stability parameter for the illumination of photo resist is the dose stability. Displayed in Fig. 8 is an accumulation of the minimum and maximum deviation from the target dose in a burst of 125 pulses. 2000 bursts were recorded for a the target dose of 0.32 J. The charging voltage was adjusted on a shot-to-shot basis for the best dose stability. Also shown for comparison is the dose stability of the previous laser at 1 kHz. The energy dose for all the measurements at 2 kHz stayed within 0.4% of the target dose whereas a deviation of 0.5% was observed with the previous laser running at 1 kHz.

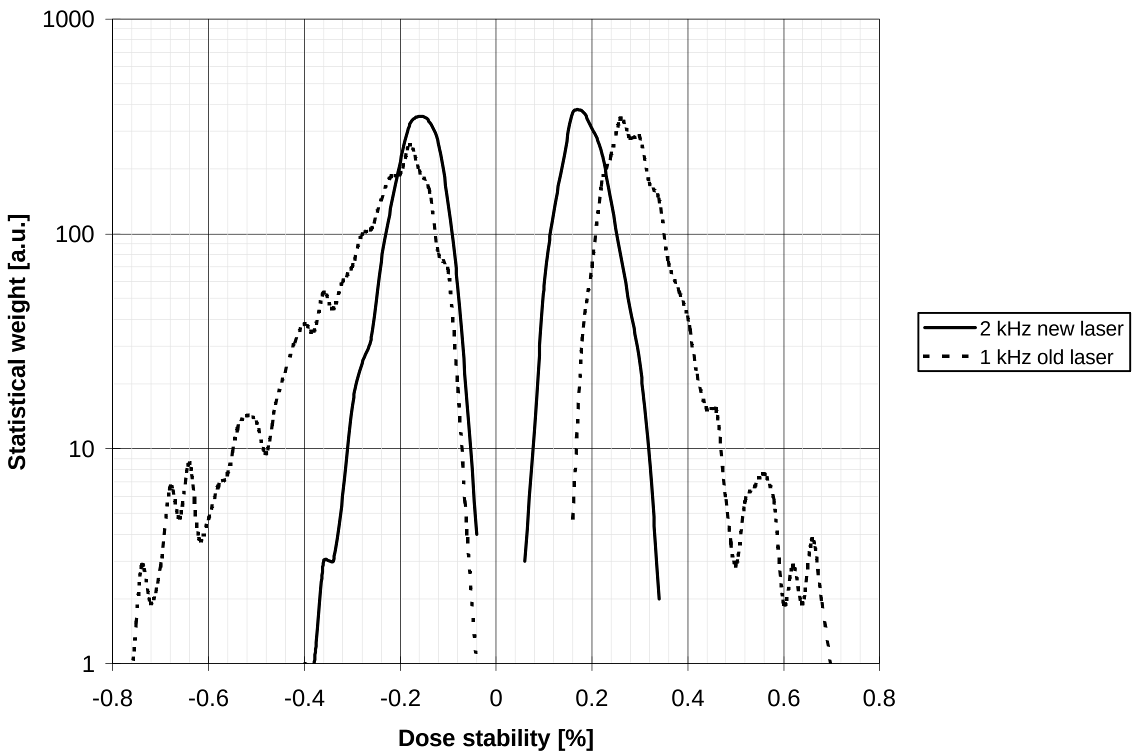

Fig. 8. Maximum deviation from the target energy for 125 pulses bursts. The data are collected for 2000 consecutive bursts.

An added benefit of the decreased charge time of the discharge capacitors is the larger useable voltage range. If the charge time is too long the gas breakdown occurs before the end of the charge cycle and any further voltage increase is wasted. Figure 9 depicts the dependence of pulse energy on charging voltage at 2000 Hz. The actual voltage on the electrodes is increased through a higher turn transformer. A total energy range of 9 mJ to 19 mJ is available. This large range helps increasing the chamber lifetime by compensating for the electrode erosion and gas aging by increasing the charging voltage.

4. CONCLUSION

We have demonstrated that present day lithography KrF lasers can be extended to spectral widths that are less than 1 pm (95% width), and that their output powers can be extended to beyond 20 W at 2kHz. Such scaling of spectral widths, power and repetition rates is possible by re-visiting some of the dynamics of evolution of laser spectrum and stability of laser discharge. The new optical line-narrowing scheme, the up-graded electrical excitation scheme and the new chamber design will result in a laser that will match the requirements of next generation laser.

30

Linewidth 0.55pm FWHM 1.70pm 95%

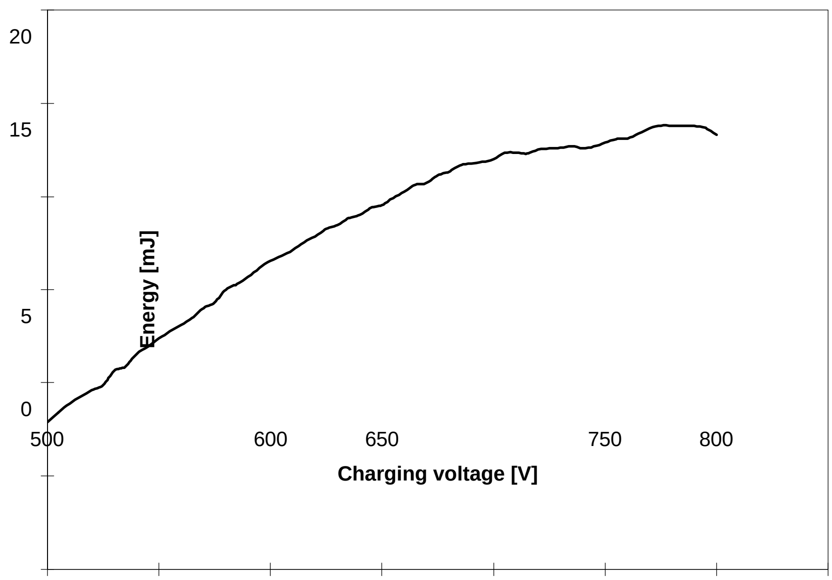

Fig.9. Dependence of laser pulse energy on charging voltage. The laser was running at 2000 Hz repetition rate.

5. REFERENCES

1. T. Farrell, R. Nunes, D. Samuels, et all, “The challenge of 1-gigabit DRAM development when using optical lithography”, *Proc. SPIE,* Vol.3051, pp. 333 -341, 1997.
2. M. Levenson, “wavefront engineering from 500 nm to 100 nm CD”, *Ibid,* pp. 2 - 13.
3. M. Op de Beeck, K. Ronse, K. Ghandehari, et all, “NA/sigma optimization strategies for an advanced DUV stepper applied to 0.25 µm and sub-0.25 µm critical levels”, *Ibid,* pp. 320 – 332.
4. G. de Zwart, M. van den Brink, R. George, et all, “Performance of a step and scan system for DUV lithography”, *Ibid,* pp. 817 – 830.
5. N. Lisi, P. Di Lazzaro, F. Flora, “Time-resolved divergence measurement of an excimer laser beam by the knife-edge technique”, Optics Communications 136, pp. 247-252, 1997.
6. P. Das, H. Heinmets, C. Maley, et all, “Reliability studies of 1 kHz KrF excimer lasers for DUV lithography”, *Proc. SPIE,* Vol.3051, pp. 933 – 939, 1997.
7. M. Sentis, Ph. Delaporte, B. Fontaine, B. Forestier, “Parametric study of X-ray preionized discharge XeCl laser at single shot and at high pulse rate frequency (1 kHz). J. Appl. Phys. 66(5), 1925 (1990)